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For the period June 15, 1969 through December 14, 1974, research on Cryogenic Instrumentation was carried out at the University of Virginia as part of project Themis. The emphasis of the program was on experimental and theoretical study of various low temperature phenomena that have device applications, particularly superconducting devices and materials. Accomplishments are reported on the following topics: → OVER

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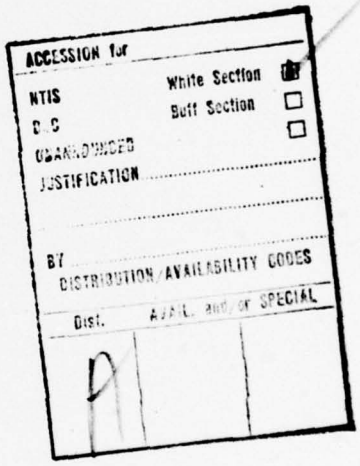
20. continued

Tunneling, Conduction and Magnetic Phenomena,
Superconductivity in Transition Metals and Transition Metal Compounds,
Device Applications of Weak Links, Fluxoid Quantization and Flux Flow,
Fundamental Fluctuation Measurements in Superconductor Microchannels,
Applications of High Q Superconducting Cavities,
Properties of Liquid Helium,
and Low Temperature Centrifugation.

Short summaries of the work are given together with lists of publications which report the details.



Final Technical Report

on

ONR Contract N00014-69-A-00429

Cryogenic Instrumentation

Submitted to

Office of Naval Research

by

Department of Physics, University of Virginia

Charlottesville, Va. 22901

March 15, 1977

Cryogenic Instrumentation

For the period June 15, 1969 through December 14, 1974, research on Cryogenic Instrumentation was carried out at the University of Virginia under contract ONR N00014-69-A-00429 as part of project Themis. The emphasis of the program was on experimental and theoretical study of various low temperature phenomena that have device applications. Support provided by this contract has been very effective in producing new results particularly in the areas of superconducting devices and materials. These results are summarized briefly below and are reported in numerous publications which are listed below.

This contract has had a very significant long range impact in establishing new capabilities at the University of Virginia which are now being exploited even more productively. Furthermore the program provided the basis for subsequent successful development of a technique for making superconducting weak links by ion implantation, for experiments that have demonstrated a superconducting detector for low energy neutral atoms, and a collaboration of members of the Physics and Electrical Engineering Departments at UVa with personnel at the National Radio Astronomy Observatory to use superconducting weak links for a Josephson mixer at frequencies greater than 100 GHz.

Two students whose doctoral research was supported largely by this contract and who worked on superconducting magnetometers and the design and construction of a prototype system for measuring the magnetic properties of materials have subsequently played a key role in the design and manufacture of commercial superconducting devices. They were two of the designers of a highly developed superconducting susceptometer that is now produced commercially, and that is currently in use in at least ten major research laboratories around the world.

As an outgrowth of this work on superconducting devices, there are tentative plans for a new course on Superconducting Electronics to be offered next year as preparation for engineers who may be involved in the rapidly developing field of superconducting devices.

During the course of the contract the research of eight faculty members, three post doctoral research associates and twenty-two graduate students was supported by the contract. Accomplishments during this period are reported below under the following topics:

I. Studies of Tunneling, Conduction and Magnetic Phenomena

II. Studies of Superconductivity in Transition Metals and Transition Metal Compounds

III. Device Applications of Weak Links, Fluxoid Quantization and Flux Flow

IV. Fundamental Fluctuation Measurements in Superconductor Microchannels and Applications of High Q Superconducting Cavities

V. Properties of Liquid Helium

VII. Low Temperature Centrifugation

Short summaries are given of the work done under each of these topics together with lists of publications which give more extensive coverage of the details.

I. Studies of Tunneling, Conduction and Magnetic Phenomena

Professors: R.V. Coleman, and S.B. Nam

Research Associates: R.C. Fivaz

Graduate Students: R.C. Morris and L. Cheskis

During the early months of the contract period theoretical and experimental studies were undertaken of some aspects of electron tunneling and conduction in solids with potential new device applications. This included work on single crystals of metals and alloys and on thin film junctions. Measurements on tunnel junctions with ferromagnetic metals showed up to six orders of magnitude change in tunnel conduction with applied voltage at helium temperature. In addition these junctions showed reproducible breakdown effects at high bias voltages and regions of negative resistance. Such junctions were successfully operated as oscillators and amplifiers.

Since this behavior was believed to be connected with magnetic oxide formed at the insulating barrier, investigations were undertaken on a variety of similar oxides and measurements were made at temperatures from 1-300 K.

Switching phenomena were observed in V_2O_3, Ti_2O_3 and Fe_3O_4. V_2O_3 and Fe_3O_4 showed a negative resistance behavior after switching and the electronic properties and stability of the negative resistance were investigated. V_2O_3 junctions were produced by oxidation of vanadium strip. Fe_3O_4 junctions were prepared both by oxidation of iron strips and by cementing electrodes to thin chips of Fe_3O_4 crystalline material.

Switching was observed in Ti_2O_3 junctions, but no negative resistance region was observed.

Junctions fabricated with Fe_2O_3, NiO and CoO barriers showed only dielectric breakdown with no evidence of reversible electronic switching.

A complete description of the experiments is given in the following:

R.C. Morris, J.E. Christopher and R.V. Coleman, "Zero Bias Anomalies in Al-Al_2O_3-Al Tunnel Junctions Doped with Fe", Phys. Letter 30A, 396 (1969).

R.C. Morris, "Conduction and Tunneling in Ferromagnetic Oxides and Junctions", Ph.D. Dissertation, University of Virginia, June 1970.

L.M. Cheskis,"Metal Insulator Transitions in Transition Metal Oxides", M.S. Thesis, University of Virginia, 1971.

Some theoretical work completed under the topic is reported in the following:

S.B. Nam, "Particle Number for a Metal with Magnetic Impurities", Phys. Letters 30A, 81 (1969).

S.B. Nam, "Transport Coefficients for Metals with Magnetic Impurities", Memorial Supplement to New Physics (Korean Physical Soc.) (Sae-Moo-Ri), 9, 39 (1969).

II. Studies of Superconductivity in Transition Metals and Transition Metal Compounds.

Professors: R.V. Coleman and R.C. Morris

Superconducting elements in the 3d, 4d and 5d transition metal series have proved to be very useful for numerous device applications. These elements are generally hard superconductors and have often not been subject to such a complete theoretical understanding as is the case for the standard soft superconductors. This is due to a number of factors both theoretical and experimental. Most of these metals have high melting points and are difficult to prepare for experimental study particularly in single crystal form. Data on the electronic structure of these metals is therefore rather incomplete as compared to the standard metals. Progress in understanding the superconducting phase is often limited by a lack of knowledge of the electronic properties and band structure of the normal phase.

The transition metals also form a number of dichalcogenide compounds which are superconducting, for example, $NbSe_2$, $NbTe_2$, NbS_2, TaS_2, $TaSe_2$, $RhTe_2$, $RhSe_2$, $CuSe_2$, CuS_2 and $MoTe_2$. A number of these form layer structures that are very anisotropic and show interesting electronic properties in both the normal and superconducting states.

Measurements of the electronic structure of a number of transition metals and transition metal compounds which have superconducting phases were made in order to understand more fully the role of d-bands in superconductivity. A general objective of this research was to characterize these superconducting compounds through a more complete knowledge of their electronic structure and to explore their special superconducting behavior for possible unique circuit behavior.

Superconducting properties such as critical field, critical current and magnetization of transition metal dichalcogenides all show a high degree of anisotropy. In addition several of these compounds can be intercalated by diffusing an organic material into the Van Der Waals gap between the layers. Such intercalation substantially increases the distance between the successive layers of metal atoms and large increases in the anisotropy of the electronic properties are observed upon intercalation.

A convenient method for studying the superconducting anisotropy in both the pure and intercalated materials consists of measuring the resistive transition which occurs as a magnetic field is applied to the specimen. This allows one to make a reasonably accurate measurement of the critical field as a function of angle.

Such measurements were made on single crystals of $NbSe_2$ at 4.2°K in magnetic fields up to 150 kOe. *The upper critical field* H_{c2} was measured as a function of the angle between the applied field and the layers of the crystal for currents flowing both parallel and perpendicular to the layers. An effective mass model based on simple considerations of the anisotropy of the crystal was used to obtain a value for the ratio of effective masses for electron motion parallel and perpendicular to the layers, and the best value obtained is $m_{11}/m_{\perp} = 0.09 \pm 0.01$. Transverse-magnetoresistance rotation diagrams were studied and structure due to flux flow and flux pinning was observed.

In addition similar measurements were made on a number of other layer structures including several intercalated with pyridine (C_6H_5N). Measurements of the angular dependence of the upper critical field H_{c2} in the transition metal dichalcogenides TaS_2, TaS_2-(pyridine), TaS_1, TaS_1Se_1-(pyridine), $TaS_{.12}Se_{.8}$ and $TaS_{.8}Se_{1.2}$ were made in magnetic fields up to 150 kOe. The observed angular

dependence was compared to simple theoretical models in order to estimate the anisotropy of the coherence length ξ in these materials. The values of the ratio $\xi_{//}/\xi_{\perp}$ calculated from the data were 20 for TaS_2-(pyridine) and approximately 7 for TaS_2, TaS_1Se_1 and $TaSe_1$-(pyridine). The alloys with different ratios of sulfur and selenium showed no major change in behavior as compared to TaS_1Se_1. The results were related to a generalized effective mass model of anisotropic electronic conduction. The resistive transitions in the intercalated materials for field orientations less than 10° from the parallel orientation are extremely broad and also exhibit unusual structure connected with enhanced flux flow resistance. The magnetoresistance behavior in the normal state of the pure and intercalated layer compounds was also measured and the changes in anisotropy due to intercalation were studied.

Also the resistivity and magnetoresistivity of $NbSe_2$ single crystals doped with iron were measured in the temperature range 1-70K. The crystals were grown with iron concentrations ranging from 0.25% to 5.0% and in zero magnetic field a strong resistance minimum is observed in the 10-15 K range followed by a relative maximum in the 1-5 K range. For magnetic fields perpendicular to the layers the increase in resistivity below the minimum is enhanced while for magnetic fields parallel to the layers the resistivity increase can be completely quenched. The detailed behavior is dependent on the iron concentration and was studied in fields up to 151 kOe. Hysteresis in the temperature dependent resistivity was observed and along with other effects suggests that some spin ordering may take place.

These results are reported more fully in the following publications:

R.C. Morris, R.V. Coleman and R. Bhandari, "Superconductivity and Magnetoresistance in $NbSe_2$", Phys. Rev. B 5, 895 (1972).

R.C. Morris and R.V. Coleman, "Anisotropic Superconductivity in Layer Compounds", Phys. Rev. 7, 991 (1973).

R.C. Morris and R.V. Coleman, "Anisotropic Superconductivity in Layered Structures", Conference on Physics and Chemistry of Layered Compounds, Monterey, California, August 1972.

R.V. Coleman, Conduction Processes in Layer Compounds", Annual Report, Francis Bitter National Magnet Laboratory, Massachusetts Institute of Technology, July 1971-June 1972.

R.C. Morris, B.W. Young and R.V. Coleman, "Anisotropic Kondo Resistance in Fe Doped $NbSe_2$", 1973 Magnetism Conference, AIP Conference Proceedings #18, p.292 (1974).

III. Device Applications of Weak Links, Fluxoid Quantization and Flux Flow

Professors: B.S. Deaver, Jr., A.S. DeReggi and S.B. Nam

Graduate Students: Edward Cukanskas, William Goodman, Anne Hafer, Max Johnson, John Pickler, Marcello Puma, Robert Rifkin, Robert Sandell, Robert Stokes and Ashley Vincent.

A general objective of this research was to investigate the use of several properties of superconductors for a variety of sensors and signal processors. Specifically the emphasis was on 1) biased weak links as combination high frequency radiation sources and detectors, 2) description and characterization of weak links as variable inductors for possible applications as parametric devices and to micro circuits, and 3) the use of weakly linked superconducting rings and cylinders for application to magnetometers and voltmeters.

Some theoretical studies of the pairing of electrons in a superconductor in the presence of a magnetic field were carried out. The results were applied to obtain the magnetic susceptibility. At a field near Hc_2, the spin susceptibility is proportional to the magnetic field. The same result was obtained also by consideration of the bound states of a superconductor. The effects of strong coupling on the spin susceptibility was also investigated and found to be ~25% for lead.

The possibility of using the biased weak link for a new kind of far infrared spectroscopy was demonstrated. It is well known that a resonant circuit with a frequency ν_o coupled to a superconducting weak-link will cause a step-like feature on the I-V curve of the weak link at the voltage V_o for which $h\nu_o = 2eV_o$. Similarly, when a substance with an electromagnetic absorption in the far infrared is coated on a superconducting point-contact, structure was observed on the I-V curve at a voltage corresponding to the absorption frequency. This suggests the possibility for a new type of

spectroscopy in an otherwise inconvenient range of frequency and using extremely small quantities of sample material.

However, with point contacts there is a profusion of additional structure already present on the I-V curves. This structure is readily observed by measuring the derivatives dI/dV vs V and d^2I/dV^2 vs V. There is a step-like structure at $V = \frac{2\Delta}{ne}$, where 2Δ is the energy gap and n is an integer. In addition there is prominent structure at voltages $>> \frac{2\Delta}{e}$. A study of the temperature dependence of all the structure shows that some features vary like $\Delta(T)$, the variation of the BCS energy gap with temperature, and others vary linearly with T^4. These variations can be interpreted in terms of a simple equivalent circuit model of a point-contact and indicate that all the features for clean point contacts are related to the Josephson Effect. An external absorber, protoporphyrin IX Fe^{3+} produced additional step-like features which did not vary with temperature over the small range of temperatures used, namely 4-9K.

These results led to another experiment to investigate the temperature dependent features. A tuned circuit resonant at frequency ν_o was coupled to a shunted superconducting point-contact. By detecting the voltage across the tuned circuit, oscillations were observed not only at the Josephson voltage $V = \Phi_o\nu_o$, where Φ_o is the flux quantum, but also at voltages $V_n = g_n(T)\Phi_o\nu_o$ where $g_n(T)$ is a continuous, monotonic function of temperature. For most temperatures $g_n(T) = N(T)/n$ where N and n are integers, however there are ranges of temperature over which $g_1(T)$ varies through non-integral values and the voltages V_n are not harmonically related. The level of oscillation of the tuned circuit was used to measure the power spectrum of the voltage waveform at the point-contact and the linewidths were found to be oscillatory functions of temperature with minima when $V_1 = N\Phi_o\nu_o$ and maxima when $V_1 = (N + \frac{1}{2}\Phi_o\nu_o)$.

The Josephson oscillation of the shunted point-contact consists of pulses of N flux quanta ($N\Phi_o$) crossing the point-contact at a repetition frequency ν_o. The temperature dependencies are interpreted in terms of fluctuations in N. These results account for the temperature dependent features that vary linearly with T^4 observed on the I-V curves of point-contacts and also have implications for noise thermometry.

For analyzing these experiments, phenomenological models and equivalent circuits to represent superconducting weak-links were used. In particular the description of a weak-link as a kinetic inductor was explored and found particularly useful for describing parametric devices. This study of various models formed the basis of a more general review of the physics of superconducting devices which was presented at the Georgetown school on the Science and Technology of Superconductivity. Subsequently an extensive review of the Josephson Effects was prepared and appeared as Chapter 5 in Volume 11 of Methods of Experimental Physics edited by R.V. Coleman. This chapter summarizes the experiments by which the Josephson Effects have been, and are being studied, describes various types of weakly-linked superconductors, gives phenomenological descriptions of each type, and discusses applications of the Josephson Effects.

Other work concerned with the response of point-contacts was also done. One set of experiments was concerned with the effects of feedback on a point-contact located at the center of a spherical metal cavity. A pronounced effect on the structure appearing at $V = \frac{2\Delta}{ne}$ where Δ is the BCS gap parameter and n an integer, was found. Other experiments observed the effects of laser and microwave radiation on point-contacts and evidence of electrodynamic pair breaking was observed. In addition, calculations using a resitively shunted Josephson junction model were found to give good agreement with the power dependence of the microwave induced structure on the I-V curves.

A third area of considerable activity has been the study of weakly-linked superconducting rings for use as magnetometers and related devices. Rings containing point-contacts and thin film rings with various types of bridges have been studied in a wide variety of different configurations ranging from a magnetometer with a 0.005-cm diameter pickup coil for mapping flux in extremely small cylinders to a complete system including persistent current magnet, superconducting shield, and magnetometer for measuring magnetic susceptibility and for nuclear resonance experiments.

A particularly successful form of magnetometer consisted of a niobium toroid with a point-contact bridging the center of the donut. By using two concentric toroidal cavities it was found that the rf drive coil and the persistent current pickup coil could be made nearly independent and that this geometry, in addition to providing extremely good shielding from external interference, provided optimum coupling to the point-contact. With a coil wound inside the toroidal cavity as the only source of signal, a magnetic flux sensitivity of $2 \times 10^{-5} \Phi_o$ was achieved. Magnetometers of this type were used to study the current phase relationship of thin film rings containing weak-links by measuring their magnetization as a function of externally applied flux through the ring.

With the very low inductance made possible by the toroidal configuration it was possible to study in detail the operation of the point contacts as an rf SQUID in the mode where the ring inductance was less than $\frac{\Phi_o}{2\pi i_c}$ where Φ_o is the flux quantum and i_c the critical current, and in the mode with the ring inductance greater than $\Phi_o/2\pi i_c$. In the former mode an asymmetry was found in the response for frequencies greater than and less than the resonant frequency of the tank circuit to which the ring was coupled. This asymmetry was found to be consistent with the phase dependent conductivity predicted by Josephson.

The phase-dependent quasiparticle current was then observed in superconducting point contacts by determining the rf impedance of phase-biased Nb point contacts. The point contact was incorporated into a superconducting ring with inductance $L < \Phi_o/2\pi i_c$, where i_c is the critical current and Φ_o the flux quantum, so that the phase difference ϕ across the link was a continuous function of ϕ_x, the magnetic flux applied through the ring. The impedance of the point contact was determined by loosely coupling the ring to the coil of a tank circuit and measuring the resonant frequency and Q at very low rf levels as a function of ϕ_x. The data give good agreement with the Josephson expression for the total current $i = i_c \sin \phi + G_o(1 + \alpha \sin \phi)V$ and require $\alpha \approx -1$ at 4.2 K and 28 MHz. The impedance measurements are being used to investigate the temperature dependence of α.

Following these experiments, a simple phenomenological description of the current in a superconducting weak link was proposed. The total current density in a weak link formed by a small metal bridge between two bulk superconductors is written as $j = n_p e v_p + n_q e v_q$, where n_p is the density of paired electrons, n_q the density of quasiparticles, and v_p and v_q the respective drift velocities. Using the fact that the pair density n_p is a function of the pair velocity and thus of the phase difference ϕ across the link, and assuming Ohm's law ($V_q \propto V$, the voltage across the link) a phase dependent conductivity is obtained. Comparison with the Josephson expression $j = j_c \sin \phi + \sigma(1 + \alpha \cos \phi)V$ yields $\alpha = -1$ at $T = 0$ and yields an approximate temperature dependence for $\alpha = -[\Delta^2(T)/2\Delta^2(0)]/[1 - \Delta^2(T)/2\Delta^2(0)]$ where $\Delta(T)$ is the BCS gap parameter. Also functional forms for $n_p(\theta)$ and $n_q(\theta)$ can be obtained and these have been used to calculate the time dependence of these quantities for current and voltage biased conditions.

An apparatus for measuring static magnetic susceptibility using a superconducting magnetometer and superconducting magnet and shields was completed and was used for susceptibility measurements and to observe nuclear magnetic resonance. Volume susceptibility changes of 10^{-10} cgs were measured with a 1 sec. response time, a 100 Oc applied field and a 1 cm^3 sample. A significant feature is that the system can be calibrated absolutely in terms of known flux. Noise limitations and potential improvements of sensitivity were studied and it appears that the system sensitivity can be improved several orders of magnitude.

The effective magnetic moments of several transition metal ions in organic compounds were studied. The effective magnetic moment of Tris (Pyrrolidyldithiocarbamato) iron III was observed to decrease from 4.11 B.M. at 4.2 K to 2.12 B.M. at 1.287 K. The replacement of various proportions of iron with cobalt showed that μ_{eff} at 4.2 K had increased and the fall off at lower temperatures was less pronounced suggesting the removal of anti-ferromagnetic interactions. The molar susceptibility at 77.3 K has been measured to be 51620×10^{-6} cgs.

The results summarized above were reported in detail in the following publications and talks:

S.B. Nam, "Pairing of Electrons in a Superconductor in a Magnetic Field", Bull. Am. Phys. Soc. (1971).

S.B. Nam, "Susceptibility of Electrons in a Superconductor", J. Korean Phys. (1971).

Wayne Donald Willis, "Flux Distribution and Quantized Flux States in Superconducting Cylinders", M.S. Thesis, June 1971.

John M. Pickler, "Modes of Oscillation of a Superconducting Point-Contact Coupled to a Resonant Circuit", M.S. Thesis, June 1971.

M. Puma and B.S. Deaver, Jr., "Self Detection of the Josephson Oscillation on Superconducting Point-Contacts", Va. Jour. of Sci. 22, 92 (1971).

W.D. Willis, W.L. Goodman and B.S. Deaver, Jr., "Distribution of Quantized Flux States in Superconducting Cylinders", Va. Jour. of Sci. 22, 93 (1971).

W.L. Goodman, W.D. Willis, D.A. Vincent and B.S. Deaver, Jr., "Quantized Flux States of Superconducting Cylinders", Phys. Rev. B4, 1530 (1971).

Marcello Puma, "Current-Voltage Characteristics of Superconducting Point-Contacts", Ph.D. Dissertation, June 1971.

M. Puma and B.S. Deaver, Jr., "Temperature Dependence of Structure on the I-V Curves of Superconducting Point-Contacts", Appl. Phys. Letters 19, 539 (1971).

B.S. Deaver, Jr., and J.M. Pierce, "Relaxation Oscillator Model for Superconducting Bridges", Phys. Letters 38A, 81 (1972).

Max Johnson, "Effects of Laser and Microwave Radiation on Superconducting Point-Contacts", M.S. Thesis, June 1973.

Ann Sutphin Hafer,"Effects of Microwave Radiation on a Superconducting Weak Link Calculated from an Equivalent Circuit Model", M.S. Thesis, June 1973.

Robert C. Stokes, "Characteristics of Superconducting Point Contacts in a Spherical Cavity", M.S. Thesis, University of Virginia, August 1973.

R.D. Sandell, J.P. Wikswo, Jr., J.M. Pickler and B.S. Deaver, Jr., "Quantized Fluctuations in the Josephson Oscillations of a Shunted Superconducting Point-Contact", J. Appl. Phys., 44, 3312 (1973).

B.S. Deaver, Jr.,"Physics of Superconducting Devices" in The Science and Technology of Superconductivity, W.D. Gregory, W.N. Mathews, Jr., and E.A. Edelsack, eds., (Plenum Press, New York, 1973), p. 539.

B.S. Deaver, Jr., and D.A. Vincent, "Experiments Using Weakly-Linked Superconductors". Chapter 5 in Methods of Experimental Physics, Vol. 11, Solid State Physics, R.V. Coleman,ed., (Academic Press, New York, 1974) pp. 199-305. (Review of the Josephson Effects and their applications, 330 refs.).

A.S. DeReggi and R.S. Stokes, "Characteristics of Josephson Point Contacts at the Center of a Spherical Cavity", Low Temperature Physics - LT 13, K.D. Timmerhaus, W.J. O'Sullivan and E.F. Hammel, eds., Vol. 3, p. 281 (Plenum, New York, 1974).

R.D. Sandell, M. Puma and B.S. Deaver, Jr., "Linewidth of Relaxation Oscillation of a Shunted Superconducting Point-Contact, Low Temperature Physics - LT 13, Vol. 3, K.D. Timmerhaus, W.J. O'Sullivan and E.F. Hammel, eds., (Plenum, New York, 1974) p. 264.

E.J. Cukauskas, D.A. Vincent and B.S. Deaver, Jr., "Magnetic Susceptibility

Measurements Using a Superconducting Magnetometer", Rev. Sci. Instrum. 45, 1 (1974).

B.S. Deaver, Jr., "Absorption Spectroscopy via the I-V Curve of a Josephson Junction", Invited paper presented at the International Conference on the Detection and Emission of of Electromagnetic Radiation with Josephson Junctions, September 1973, Perros-Guriec, France. (Revue de Physique Appliquée 9 297 (1974)).

D.A. Vincent and B.S. Deaver, Jr., "Observation of a Phase-Dependent Conductivity in Superconducting Point-Contacts", Phys. Rev. Letters 32, 212 (1974).

D.A. Vincent, "Experimental Studies of Superconducting Rings Containing a Single Weak Link", Ph.D. Dissertation, May, 1974.

E.J. Cukauskas, "Magnetic Susceptibility Measurements Using Superconducting Devices", Ph.D. Dissertation, August 1974.

R.D. Sandell, Temperature Dependence and Spectral Analysis of Josephson Oscillations of a Shunted Superconducting Point-Contact", Ph.D. Dissertation, August 1974.

B.S. Deaver, Jr., R.D. Sandell and D.A. Vincent, "A Simple Phenomenological Approach to the Phase-Dependent Conductivity of a Superconducting Weak Link", Physics Letters 46A, 411 (1974).

D.A. Vincent and B.S. Deaver, Jr., "Measurements of the Josephson Cos ϕ Term in Phase-Biased Point Contacts, Bull. Am. Phys. Soc. 19, 204 (1974).

R.D. Sandell and B.S. Deaver, Jr., "A Simple Phenomenological Description of the Current in a Superconducting Weak Link", Bull. Am. Phys. Soc. 19, 204 (1974).

E.J. Cukauskas, E.Sinn and B.S. Deaver, Jr., "Low Temperature Studies of Some Transition Metal Compounds Using a Superconducting Susceptometer", Bull. Am. Phys. Soc. 19, 229 (1974).

P.J. Osina and B.S. Deaver, Jr., "New Features of the Raman Spectrum of Liquid Ammonia", Bull. Am. Phys. Soc. 19, 237 (1974).

E.J. Cukauskas, B.S. Deaver, Jr., and E. Sinn, "A New Mode of Antiferromagnetic Interactions: Tris (Pyrrolidyldithicarbomato) Iron (III)", J.C.S. Chem. Comm. 698 (1974).

E.J. Cukauskas, E. Sinn and B.S. Deaver, Jr., "Observation of High Spin - Low Spin Crossover, Antiferromagnetic and Ferromagnetic Interactions in Tris (Pyrrolidyldithiocarbomato) Iron III", Bull. Am. Phys. Soc. 19, 1120 (1974).

R. Rifkin, "Radio Frequency Measurements on a Superconducting Ring Containing a Single Weak Link", Ph.D. Dissertation, August 1975.

IV. Fundamental Fluctuation Measurements in Superconductor Microchannels and Application of High Q Superconducting Cavitier.

Professor: John M. Piece

Graduate Students: John Miller and Gordon Spencer

The main thrust of the work has been the elucidation of fundamental thermodynamic fluctuations which become evident near the transition in constricted superconducting channels. These fluctuations will set ultimate limits on the sensitivity obtainable in superconducting weak-link devices which are based on repetitive transitions in such constricted channels. The approach has been through studies of the complex impedance of small diameter tin whisker crystals in the hope than an understanding could be reached of the fluctuations in these clean, well-characterized systems which could then be applied to less well-characterized channels such as point-contacts and microbridges.

An extensive experimental study of fluctuation effects in the complex ac impedance $Z_W(\omega,T)$ of one-dimensional tin whisker crystals near the superconducting transition temperature T_c was completed. The behavior of $Z_W(\omega,T)$ in <001> whiskers with cross-sectional areas 2×10^{-10} - 3×10^{-9} cm^2 was measured at 60 MHz, 1 kHz, and dc from below T_c in the mean field temperature range up through T_c and slightly above. Paraconductivity data were not obtained. By correlating high frequency reactance data with resistance data from dc or low-frequency ac measurements, a more stringent test was made of the theory of fluctuation effects than is possible with dc measurements alone. The theory of Langer and Ambegaokar (LA) as completed by McCumber and Halperin (MH) for the onset of resistance in inconsistent with the results unless the LA barrier height is reduced by a factor of approximately 0.55. If this is done, LA-MH prediction agrees with resistance data over the full whisker size range. The MH result for the onset of fluctuation effects in

the reactance agrees with the data without modification. No theory exists which can explain the behavior of $Z_W(\omega,T)$ as T passes through T_c. The data has been reported in a form to facilitate comparison with future theories. Reactance data in the mean field region yield a direct measurement of the penetration depth. An interesting size effect in this quantity was found, and a new value is reported for the London penetration depth in pure tin, $\lambda_L = 289 \pm 20$ Å.

As a parallel effort a series of measurements of the response of superconducting films to strong microwave frequency fields near T_c was made. These measurements were designed to help elucidate the dynamics of the superconducting order parameter in response to a time varying field. This response is of course crucial to the behavior of weak link devices which operate with a time dependent order parameter. The first question the experiments were designed to answer relate to the conditions under which a superconductor will change from an adiabatic response, where the order parameter follows changes in a varying field, to an integrating behavior where the order parameter responds to an average field with very little time varying part. Such a switch in behavior was predicted theoretically, and it can be observed by placing a film of the superconductor near the wall of a micro-wave cavity made of a higher temperature superconductor. Changes in film behavior are reflected in the cavity resonant frequency and Q.

Measurements were made using a gunn diode oscillator frequency locked to a Nb cavity with unloaded Q of 16×10^6. The initial data give very pronounced structure on the Q vs temperature data just below T_c for the Sn sample film.

In the course of this work it became apparent that the explosive advances in the art of making high quality superconducting micro-wave resonators which occurred in the previous decade had not been widely appreciated outside the

accelerator community where the work had been done. Since Dr. Pierce has been closely associated with this field in the past and since much of the work which had resulted in the advances in the art had been supported by ONR, it seemed appropriate for him to take some time under this contract to write a review article on superconducting micro-wave resonators for general audience. This review and other publications describing this research are listed below:

J.M. Pierce, "Complex Impedance Measurements on Superconducting Tin Whisker Crystals," Bull. Am. Phys. Soc. 15, 1353 (1970).

J.R. Miller and J.M. Pierce, "Measurements of the Complex Impedance of Superconducting Tin Whisker Crystals near T_c," Bull. Am. Phys. Soc. 17, 333 (1972).

J.M. Pierce and J.R. Miller, "A High Frequency Heterodyne Lock-in-Amplifier", Rev. Sci. Instr. 43, 1721 (1972).

J.M. Pierce, "The Residual Microwave Surface Resistance of Superconducting Lead," J. Appl. Phys. 44, 1342 (1973).

J.R. Miller and J.M. Pierce, "Fluctuation Effects in the Complex Impedance of Superconducting Tin Whisker Crystals Near T_c," Phys. Rev. B8, 4164 (1973).

J.R. Miller, "Measurements of the Complex Impedance of One-Dimensional Tin Whisker Crystals Near the Superconducting Transition Temperature," Ph.D. Dissertation, University of Virginia, June, 1973.

J.R. Miller and J.M. Pierce, "Fluctuation Effects in the A.C. Impedance of One Dimensional Superconductors," Low Temperature Physics, LT13. K.D. Timmerhaus, W.J. O'Sullivan, and E.F. Hammel, Editors, Vol. p. (Plenum, New York, 1974).

J.M. Pierce, "Superconducting Microwave Resonators," Chapter 10 in Methods of Experimental Physics, Vol. II, R.V. Coleman, Ed., (Academic Press, New York, 1974).

Gordon L. Spencer, "Measurements of the Surface Impedance and the ac Critical Field of Superconducting Thin Tin Films at 10 GHz," Ph.D. Dissertation, University of Virginia, Nov. 1975.

V. Properties of Liquid Helium

Professors: G.B. Hess and F.E. Moss

Graduate Student: D.M. Sitton

Mechanisms of breakdown of superfluid flow in liquid helium II were studied by Professor G.B. Hess. The rate of flow of superfluid helium through 10-micron diameter holes in nickel foil has been measured. Ordinarily the average velocity in the orifice is of the order of 30 cm/sec and independent of temperature. However when the orifice is enclosed by superfluid filters of compressed jewelers rouge, velocities up to 550 cm/sec were seen, with temperature dependence similar to the "intrinsic" critical velocity previously seen by Reppy and co-workers and by Notarys on much smaller channels. Subsequent measurements found similar "intrinsically-limited" flow in a 35 micron diameter orifice, although the slower, "extrinsic" mode occurs often.

These results are reported in the following publication:

G.B. Hess, "Critical Velocities in Superfluid Helium Flow through 10-μm-Diameter Pinholes", Phys. Rev. Letters 27, 977 (1971).

Studies of the properties of liquid helium were also carried out by Professor Frank Moss and D.M. Sitton. Their work centered on the study of turbulent helium II.

The structure of bulk, superfluid helium in the presence of a super-critical heat current from an incandescent filament was studied using negative ions as probe particles. The ions were produced by thermionic emission of electrons from the filament of a cylindrical diode. Vorticity within the diode was charged by applying a negative voltage to the filament. Both initially free ions and trapped ions escaping from the vorticity were observed by reversing the voltage. New measurements of the ion-vortex line escape probability, which are in agreement with the escape theory of Donnelly, were

obtained in a higher temperature range than previously reported. Measurements of the total trapped charge support a theory of Vinen on the structure of turbulent He II. The individual vortex lines are found to be identical to those produced by rotation except for spatial configuration.

In searching for a suitable ion source to study turbulence they investigated the properties of field emission points and strong tritium sources. The mobility of both positive and negative charges near T_λ were measured with the result being that the mobilities follow a 2/3 power law suggesting that the mobilities are determined by fluctuations near the λ point.

One study of turbulence involved measurements of the escape of negative ions from pressurized turbulent He II and initial measurements were made of the escape of negative ions resulting from the annihilation of two oppositely circulating vortex lines. This research is described in several publications listed below:

D.M. Sitton, "Trapping of Negative Ions in Turbulent Superfluid Helium," M.S. Thesis (Engineering Thesis), Univ. of Va, 1970.

D.M. Sitton and Frank Moss, "The Structure of Turbulent Superfluid Helium," Low Temperature Physics LT12 (Academic Press of Japan, Tokyo, 1971) p. 109.

D.M. Sitton and F. Moss, "Free Ion Mobility in He 11 Using Field Emission Points," Phys. Letters 34A, 3 (1971).

Donald M. Sitton and Frank Moss, "Observation of the Escape of Negative Ions from Pressurized Turbulent He II," Phys. Rev. Letters 29, 542 (1972).

D.M. Sitton, "Ion Motion in Superfluid Helium Using Space Charge Limited Currents," Ph.D. Dissertation (Engineering Dissertation), Univ. of Va, 1972.

VI. Low Temperature Centrifugation

Professor J.W. Beams developed a technique for spinning rotors of almost any size up to rotational speeds limited only by their strength, at liquid helium temperatures. The rotor is spun on the lower end of a long vertical stainless hypodermic needle tube which connects to an air turbine drive above the apparatus. The electrical leads from the rotor are brought out through the hollow shaft and liquid mercury contacts. A convenient low noise system of liquid mercury electrical connections was also developed.

The possible effect of a centrifugal field and/or high speed rotation on the superconducting transition temperature of niobium wire was searched for. The experiments indicated no shift larger than 0.3K occured in a centrifugal field of 5×10^{-4}g.

The technique is described in the following publication:

J.W. Beams, "Improved Method of Spinning Rotors to High Speeds at Low Temperature," Review of Scientific Instruments 42, 637 (1971).

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